# Flight Control System Mode Transitions Influence on Handling Qualities and Task Performance

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**The Flight Research Simulator of the University of Toronto Institute for Aerospace Studies was modified to represent a fly-by-wire helicopter with a digital flight control system (FCS) and a side-arm controller. Three FCS modes were employed (in addition to the basic airframe version of the helicopter): rate command/attitude hold, attitude command/attitude hold, and translational rate command. A smooth FCS mode selection algorithm was developed and successfully tested. Three types of mode transition were evaluated: 1) transition selected manually by the pilot, 2) transition selected by the FCS accompanied by an audio warning, and 3) transition initiated without warning by a system failure. The pilot/helicopter response to mode transitions was studied for formation flying and precision hover. Both normal- and failure-induced transitions were investigated by a group of 9 evaluation pilots. The results were obtained in the form of Cooper-Harper handling qualities ratings (HQR) and stationkeeping performance measurements. It was found that for the present mode selection algorithm, the type of mode transition from the initial FCS mode to the final FCS mode (i.e., within a mode pair) did not significantly influence the experimental results. However, the mode pair itself was found to influence both HQRs and performance. The mode pairs producing most of the significant effects on HQR and performance contained as one of their elements, the FCS mode having the poorest handling qualities. For mode pairs producing significant effects, it was found in some instances that the mode in place before transition actually influenced the HQRs and performance after transition.**

## Introduction

THE incorporation of digital flight control systems (FCS) in aircraft allows the development of highly augmented systems (modes) to aid the pilot in the performance of a wide range of complex tasks.[1] As a mission unfolds the pilot may be required to switch between FCS modes in order to select the one most suited to the task at hand.[2] A mode selection algorithm is required to carry out these commanded mode transitions. Because the effective vehicle dynamics for these modes can be significantly different, care must be taken to ensure that the mode transitions themselves do not adversely affect the vehicle's flying qualities. An experiment was carried out to investigate the influence of mode transition type and mode pair (initial mode combined with final mode) on handling qualities and system performance.[3] The study employed the UTIAS Flight Research Simulator configured to represent a modified Bell 205 helicopter.

## Simulator Configuration

The UTIAS Flight Research Simulator incorporates a cab mounted on a 6 degrees-of-freedom CAE Series 300 motion base. The forward visual display scene is generated by a Silicon Graphics 4D/310VGX computer. This display employs an infinity optics window box providing a field-of-view 29 deg (vertical) by 40 deg (horizontal). Figure 1 is a photograph of the pilot's workstation. In the present study the center stick was not used. The pilot's pitch and roll commands were entered via a compliant side-arm controller. The electronic flight instrumentation system (EFIS) can be seen in the picture. It was located immediately below the window box. The simulator was operated at a 30-Hz update rate.

## Flight Control System

The flight control system was implemented as shown in Fig. 2. In this figure $\delta$ are the pilot commands to the FCS, $d$ are the swashplate and tail rotor inputs to the helicopter, and $x$ is the helicopter state vector. The FCS closed a loop around the Bell 205 (already augmented by increased pitch and roll damping). The modes employed were selected based on material presented in Ref. 2. Here, the mode designation applies to both the pitch and roll response types active in the mode.

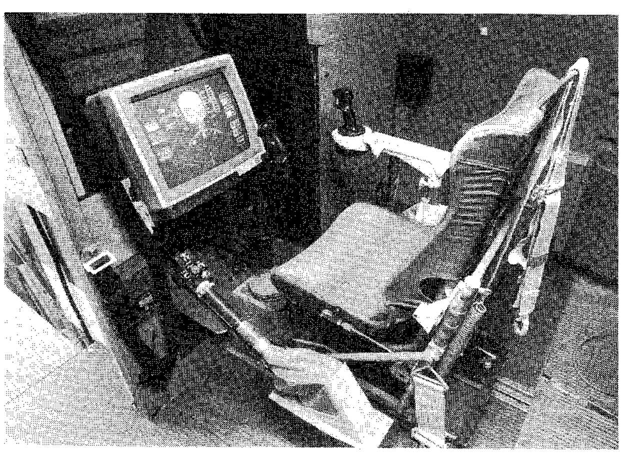

**Fig. 1 Helicopter simulator cockpit.**

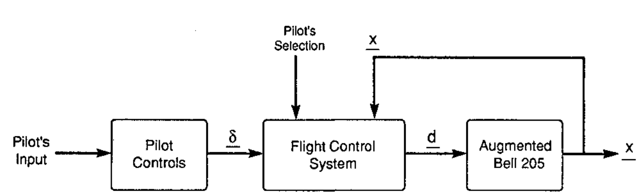


**Fig. 2 Flight control system.**

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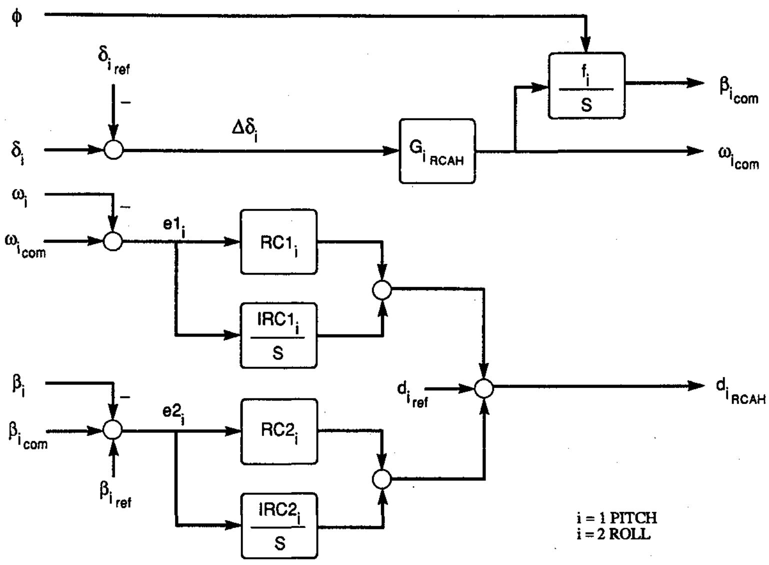


**Fig. 3 RCAH mode.**

The modes for the formation task were basic airframe (BA) consisting of the augmented Bell 205, rate command/attitude hold (RCAH), and attitude command/attitude hold (ACAH). In the latter two modes the heave response type was vertical rate command/height hold and the yaw response type was turn coordination (flown with no pilot pedal inputs). The modes for the hover task were translational rate command (TRC), RCAH, and ACAH. In all of these hover modes the heave response type was vertical rate command/height hold and the yaw response type was heading rate command/direction hold.

A smooth mode selection algorithm was implemented that produced transient-free mode transitions for the flying tasks employed in this study.[4] Its functioning can be understood by looking at the pitch and roll channels of the RCAH mode as shown in Fig. 3. When the RCAH mode is selected the control system samples the current values of the pilot controls $\delta_i$, the current pitch and roll attitudes $\beta_i$, and the current swashplate commands $d_i$. These are then used as new reference values $(\ )_{\text{ref}}$ in the FCS as shown in the figure. The new swashplate input is then immediately taken to be $d_{i_{\text{RCAH}}}$. The incremental attitude hold signal comes from

$$\beta_{i_{\text{com}}} = \int f_i(\phi)\omega_{i_{\text{com}}}\, \mathrm{d}t \tag{1}$$

where $\omega_{i_{\text{com}}}$ is the commanded pitch or roll rate, $\phi$ is the bank angle and

$$f_1 = \cos\phi \tag{2}$$

$$f_2 = 1 \tag{3}$$

The initial value of the integral is set to zero when the RCAH mode is selected. Therefore, immediately following the mode transition

$$\beta_{i_{\text{com}}} = \omega_{i_{\text{com}}} = 0 \tag{4}$$

and if no control input changes are made by the pilot, the vehicle attitude will steady out at

$$\beta_i = \beta_{i_{\text{ref}}} \tag{5}$$

and the pitch and roll rates will decay to zero. This scheme produced very smooth mode transitions in the present experiments.

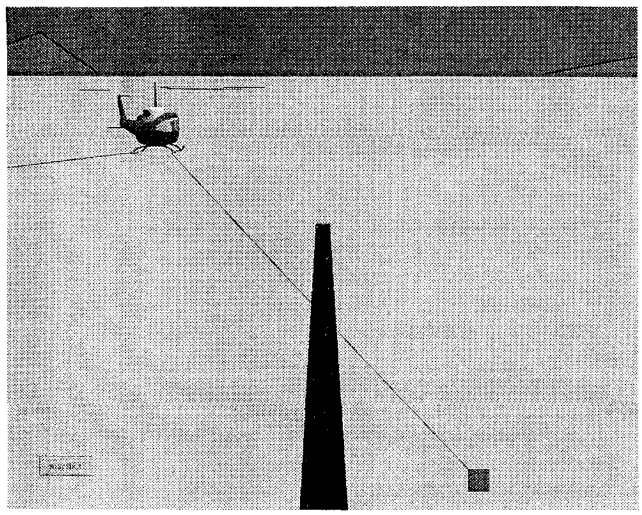

**Fig. 4 Formation task scene.**

## Flying Tasks

In order to assess the ability of pilots to handle mode transitions it was necessary to develop flying tasks during which the transitions occurred. Two tasks were selected: 1) formation flying to represent high-speed control, and 2) precision hover to represent low-speed control.

### Formation Flight

The formation task consisted of flying formation with another Bell 205 helicopter. The lead helicopter flew straight and level at an altitude above ground level of 500 ft and a constant airspeed of 100 kt. The pilots began by establishing a steady formation to the right (left) of the lead helicopter and then following a first audio tone (66 s after the start of the test), crossed over to the left (right) of the lead helicopter, and re-established a steady formation for a further 33 s. The pilots were instructed to achieve a maximum bank angle of 5 deg during the maneuver. The flight control mode at the start of the flight was determined by the experimenter. As the following helicopter passed the vertical plane of symmetry of the lead helicopter, one of several mode transitions occurred.

In order to ensure that all of the pilots flew formation at approximately the same position relative to the lead aircraft, several aids were provided. A nose boom was affixed to the following helicopter. This appears in the lower portion of Fig. 4 as seen by the test pilot. The tip of the 8-cm-wide boom was directly in front of the pilot and located 4.9 m forward of and 0.6 m below his eye position. The lead helicopter trailed two target squares (20 × 20 cm) from the rear of its skids as shown in Fig. 4. The targets were positioned 0.6 m below the lead pilot's eye position, 13.4 m to the side of the vertical plane of symmetry and 47.2 m behind the rotor mast. The proper location for the following helicopter while in formation placed the tip of the boom 7.5 m behind the target square. The pilots were instructed to maintain formation by observing the lead aircraft and to use the target square only as a general guide to the desired location.

During these flights the following helicopter flew through undisturbed still air. The flight began with the following helicopter in approximately trimmed flight near the desired initial formation location.

#### Precision Hover

In this task the pilot was required to hover in front of a row of trees in the presence of turbulence. In particular he was to attempt to position a nose boom on his helicopter near to the top of a specific tree. The tip of the 8-cm-wide boom was directly in front of the pilot and located 4.9 m in front of and 0.3 m above his eye position. The trees were representative three-dimensional objects 9.14 m high and 1.32 m wide at the base. They were laid out in a regular grid pattern separated laterally 3.05 m in four rows spaced apart by 30.48 m. The entire scene is shown in Fig. 5. Two trees in the front row (the row closest to the pilot at the start of the task) were marked with yellow bands near their top. The pilot was to start by hovering on the right (left) marked tree and then following an initial audio tone (66 s after the start of the test) cross over to hover on the left (right) marked tree for a further 33 s. The pilots were instructed to achieve a maximum bank angle of 5 deg during the maneuver. The marked trees were the second trees to the right and left of the center tree in the row. As the helicopter passed the center tree of the grid of trees one of several mode transitions could occur.

The helicopter was disturbed by a set of random signals described in Ref. 5. The pilots regarded them as turbulence inputs. The intensity levels were selected to produce turbulent wind components in the three orthogonal directions, all having the same rms level of 2.3 m/s.

The flight began with the helicopter aligned with the tree grid and facing the marked tree to be used for the initial hover. The distance from the pilot's eye to the tree was 83.6 m. The initial flight conditions were a forward ground speed of 2 kt, an altitude (skid height) of 45 ft (13.7 m), and a slight rate of descent.

The nominal hover height (which placed the boom tip at the same height as the tree tops), was achieved at an indicated skid height of 20 ft (6.1 m). The nominal hover location was in line with the designated tree and back from it a sufficient distance to allow the neighboring trees on either side to be visible in the simulator visual display. Given the display's 40-deg lateral field-of-view, this placed the boom tip 3.5 m from the centerline of the tree.

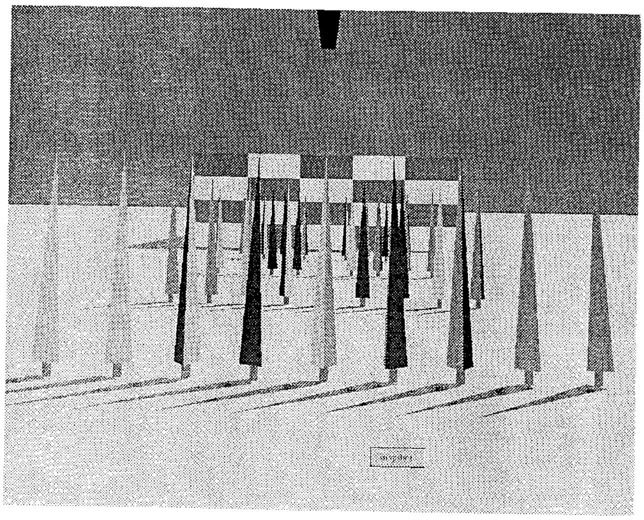

**Fig. 5 Hover task scene.**

### Mode Transition Type

Three mode transition types were selected for study. In the manual transition test the experimenter told the pilot before the flight which mode he was to select when prompted by the second audio tone. The initial control mode was one selected by the experimenter and displayed to the pilot. As the helicopter crossed the centerline during the maneuver the second audio tone sounded, at which point the pilot was to manually select the new mode (using a switch mounted on the collective lever) as previously instructed by the experimenter. The audio tone remained on until the correct mode was selected (the computer blocked all other modes).

If the task does not involve a manual transition, then the pilot is given no instructions prior to the flight. In this case one of three equally likely conditions may apply. There may be no transition, in which case the pilot receives no audio tone as he passes through the centerline and the initial flight control system mode remains unchanged. All other task details remain the same. There may be a FCS selected mode transition with warning. In this case as the pilot passes through the centerline a brief audio tone sounds and a mode transition is initiated by the computer. The new mode is correctly displayed on the EFIS. All other task details remain the same. Finally, there may be a simulated system failure without warning. In this case, as the pilot passes through the midpoint plane, a mode transition is initiated by the computer with no audio warning. The initial mode remains displayed on the EFIS. All other task details remain the same.

In all of the above scenarios the only time that the pilot's mode selection switch is operational is during the manual transition case.

### Experimental Plan

The mode transition types evaluated are represented by the symbols TN, TM, TS, and TF according to the following:

TN = no transition
TM = manual (pilot selected) transition
TS = system selected transition with audio warning
TF = failure induced transition

In the formation task, six mode pair combinations were employed: 1) ACAH → BA, 2) ACAH → RCAH, 3) BA → ACAH, 4) BA → RCAH, 5) RCAH → ACAH, and 6) RCAH → BA. In the hover task, the six mode pairs were: 1) TRC → ACAH, 2) TRC → RCAH, 3) ACAH → TRC, 4) ACAH → RCAH, 5) RCAH → TRC, and 6) RCAH → ACAH. Before participating in the experiment, all pilots were thoroughly trained on all the tasks. Each of 9 evaluation pilots flew all 48 task combinations once. Following training, each pilot was randomly assigned to both a formation and a hover task block of runs. Within each block, the order of presentation of run type (made up of transition type and mode pair) was also randomized. In addition, each run was randomly selected to start from either the left or right side.

Nine male pilots volunteered to participate in the experiment. Their backgrounds are outlined in Table 1. Based on their experience they were divided into three groups of three according to G1—active test pilots, G2—pilots with flight test backgrounds, and G3—pilots without flight test backgrounds.

Both subjective and objective evaluations of the flying tasks were obtained. The subjective results were Cooper-Harper handling qualities ratings (HQR) assigned according to the

**Table 1 Pilot experience**

| Group | Pilot code | Age, yr | Training background | Test pilot training | Fixed wing Aircraft hours | Fixed wing Simulator hours | Helicopter Aircraft hours | Helicopter Simulator hours |
|---|---|---|---|---|---|---|---|---|
| G1 | *A* | 57 | Military | Yes | 6000 | 450 | 2500 | 250 |
| | *B* | 54 | Military | Yes | 9000 | 120 | 1700 | 58 |
| | *C* | 29 | Military | Yes | 1100 | 25 | 1900 | 35 |
| G2 | *D* | 35 | Military | Yes | 500 | 50 | 2700 | 10 |
| | *E* | 40 | Civil | No | 1450 | 50 | 600 | 0 |
| | *F* | 44 | Military | Yes | 1400 | 24 | 2300 | 95 |
| G3 | *G* | 34 | Military/civil | No | 3500 | 150 | 1600 | 0 |
| | *H* | 36 | Civil | No | 30 | 10 | 5000 | 0 |
| | *I* | 40 | Military | No | 900 | 0 | 1500 | 30 |

recommendations of Ref. 6. The pilots were asked to rate only that part of the flight following the crossing of the centerline (either lead helicopter or center tree), including any mode transition effects.

The objective measure is $\sigma$, the standard deviation of the absolute distance from the helicopter boom tip to the designated towed target or target treetop. $\sigma_1$ is the value based on performance from 33 s after the start of a run until the first audio tone sounds 33 s later. $\sigma_2$ is the value based on performance following the crossing of the centerline until the end of the run 33 s later. Thus, $\sigma$ is influenced both by the time taken to establish the stationkeeping point and the precision with which it is maintained.

There was no feedback of performance results to the pilots after each run. If requested, the pilots were told the second mode type once they had given their HQR for the run.

The training and production runs for each pilot took place during 2–5 days. Each production run took approximately 2 min, and was followed by a 2-min interval during which the HQR was obtained. Typically 12 runs were performed in 45 min, followed by a 15-min rest during which the pilot came out of the simulator.

## Results

### Formation Flight

Figure 6 is an example of the boom tip trajectory (as seen from above) produced during one of the formation flight production runs. $X$ is zero when the boom tip is at the fore and aft location of the towed targets, and is positive when it is in front of the targets. $Y$ is zero when the boom tip is in the plane of symmetry of the lead helicopter, and is positive when it is to the right of this plane. The plot covers that part of the run from 33 s into the task to the end. The task involved a TS transition from RCAH to ACAH.

Figure 7 gives averaged HQR values (along with the range) for the formation task for the TN case. It can be seen that the RCAH mode had significantly poorer handling qualities than the other modes. This was intentional. The stick gains for the RCAH mode were set to uncomfortably high levels to produce this. The purpose was to achieve mode pairs that would represent transitions between modes with different HQRs in order to study the effect of this factor along with mode transition type.

The HQR data were analyzed using Dunn's multiple comparison test[7] to determine the effect of transition type on ratings. This statistical test allows one to determine which average results taken two at a time can be considered to be different from one another. The results for the formation task are reported in Table 2. The mode transition types are indicated as headings for the rows and columns of the table. To determine the significance of the difference between the HQR results from two different mode transition types, choose one type from the four rows and follow across the row to the column representing the second transition type. The larger the number in that cell, the more statistically significant is the difference between the two results. The data under the HQR

**Table 2 HQR, Dunn's multiple comparison TN/TM/TS/TF formation task**

| | HQR | TN | TF | TS | TM |
|---|---|---|---|---|---|
| TN | 3.52 | —— | 2.64[a] | 2.81[a] | 3.85[a] |
| TF | 4.10 | —— | —— | 0.17 | 1.21 |
| TS | 4.14 | —— | —— | —— | 1.05 |
| TM | 4.37 | —— | —— | —— | —— |

Note: Mode pairs grouped together; $df = 212$, $C = 6$, $tD_{0.025} = 2.64$.
[a]Significant at the 5% level.

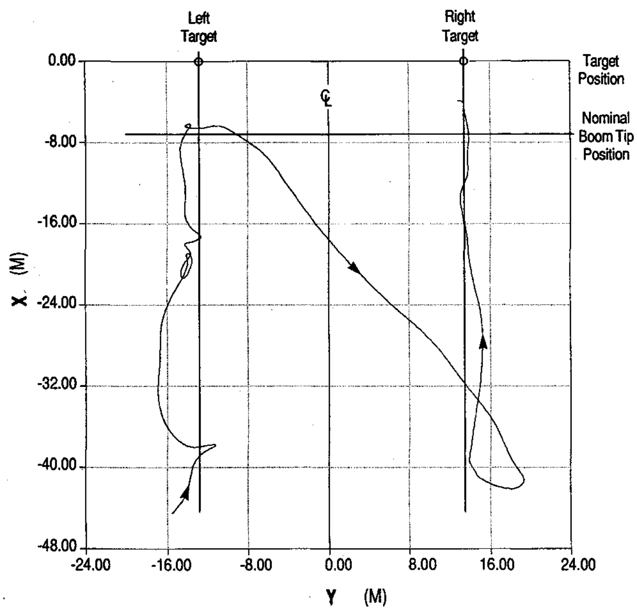


**Fig. 6 Formation task: Boom tip path (for TS, RCAH → ACAH).**

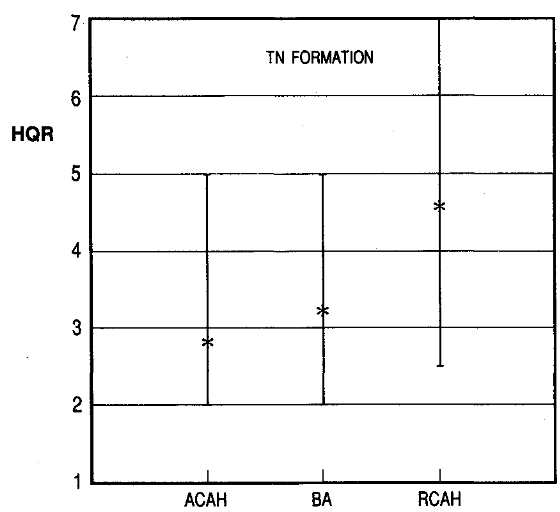


**Fig. 7 Mean and range of HQR for TN, formation task.**

heading are the average HQR results for each mode transition type. It is seen that at the 5% significance level TN has better HQR than all the other transition types.

A standard analysis of variance (ANOVA) was carried out on the formation task HQR data based on the three factors (transition types TM, TS, and TF) × (mode pair) × (pilot group). The results are presented in Table 3. It is seen that pilot group is the only significant factor and that there are no significant interactions among the factors. Thus transition type and mode pair do not influence the HQR ratings for the formation task. The absence of interactions means that all three pilot groups produced the same trend in HQR relative to the other experimental factors. In absolute terms, approximately one-half rating point separated G1 from G2 and G2 from G3. The active test pilots (G1) gave the least favorable ratings, whereas the pilots without flight test backgrounds (G3) gave the most favorable ratings. This can be seen in Fig. 8.

The mean of the performance data $\sigma_1$ and $\sigma_2$ for the formation task are plotted in Fig. 9. An analysis of variance applied to $\sigma_1$ for the formation task (using the same three factors employed above) indicated no significant effects nor interactions. The same test applied to $\sigma_2$ showed that mode pair was significant at the 10% level. The trend of $\sigma_2$ with respect to mode pair can be seen in the figure. Unexpectedly, mode pairs starting with RCAH produced the poorest performance $\sigma_2$ after mode transition. This indicates that it was more difficult for the pilots to alter their control strategy when initially flying a marginally acceptable configuration than was the case when initially flying a reasonably well-behaved configuration. Further testing is needed to confirm the reasons for this effect.

**Table 3 HQR, ANOVA**

| Effect | $df$ | Sum of squares | $F$ | $P(x > F)$ |
|---|---|---|---|---|
| Transition | 2 | 2.287 | 0.984 | 0.39 |
| Mode pair | 5 | 6.519 | 1.122 | 0.38 |
| Group | 2 | 21.954 | 9.446 | <0.01[a] |
| $T \times M$ | 10 | 11.806 | 1.016 | 0.46 |
| $T \times G$ | 4 | 2.954 | 0.635 | 0.64 |
| $M \times G$ | 10 | 11.972 | 1.030 | 0.45 |
| $T \times M \times G$ | 20 | 14.287 | 0.615 | 0.86 |
| Residual | 108 | 125.5 | —— | —— |

Note: (Transition: TM, TS, TF) × (mode pair) × (pilot group) formation task.
[a]Significant at the 1% level.

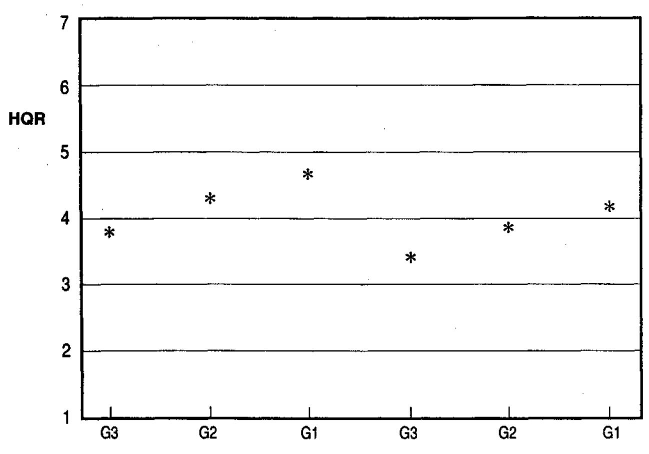


Fig. 8 Pilot group effects. Mean HQR data.

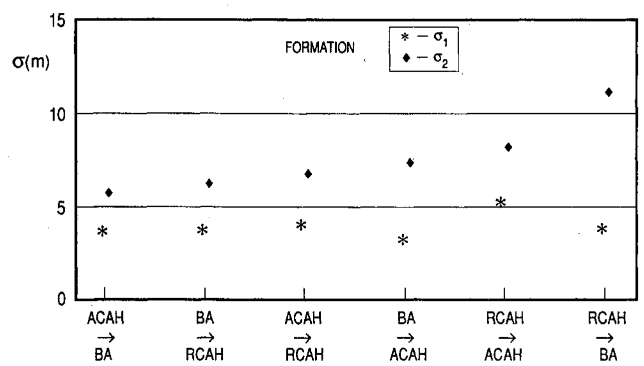


Fig. 9 Mean performance $\sigma_1$ and $\sigma_2$ for formation task.

### Precision Hover

Figure 10 gives a typical boom tip trajectory (as seen from above) for a hover task production run. $X$ is zero when the boom tip is at the fore and aft location of the tree line, and it is positive when it is behind the trees. $Y$ is zero when the boom tip is located at the center tree in the row, and it is positive when to the right of this tree. The plot covers that part of the run from 33 s into the task to the end. The task involved a TM transition from TRC to RCAH.

Figure 11 gives averaged HQR values (along with the range) for the hover task for the TN case. When Dunn's multiple comparison test was applied to the HQR data for the mode transition types no significant differences were found at the 5% level.

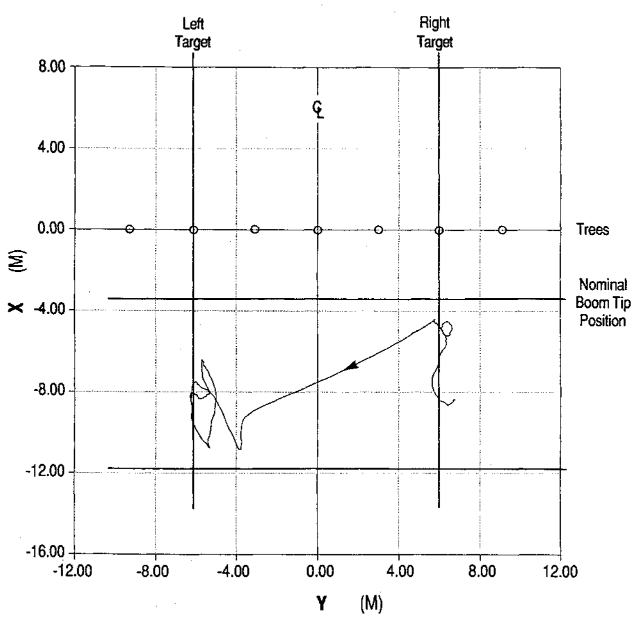


Fig. 10 Hover task: boom tip path (for TM, TRC → RCAH).

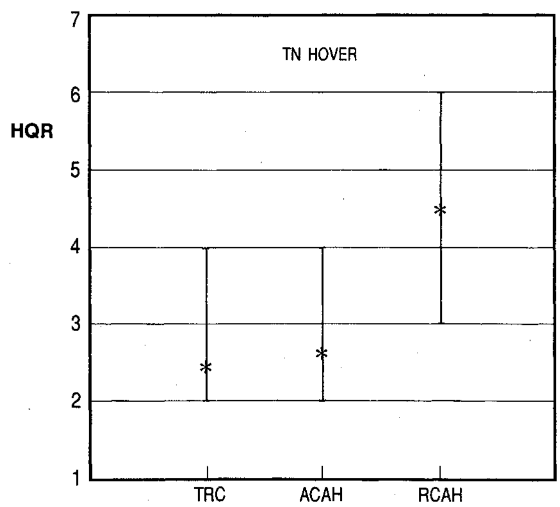


Fig. 11 Mean and range of HQR for TN, hover task.

**Table 4 HQR, ANOVA**

| Effect | $df$ | Sum of squares | $F$ | $P(x > F)$ |
|---|---|---|---|---|
| Transition | 2 | 0.799 | 0.558 | 0.58 |
| Mode pair | 5 | 173.952 | 48.587 | <0.01[a] |
| Group | 2 | 16.040 | 11.200 | <0.01[a] |
| $T \times M$ | 10 | 3.238 | 0.452 | 0.90 |
| $T \times G$ | 4 | 2.080 | 0.726 | 0.58 |
| $M \times G$ | 10 | 2.664 | 0.372 | 0.94 |
| $T \times M \times G$ | 20 | 8.994 | 0.628 | 0.85 |
| Residual | 108 | 77.3 | —— | —— |

Note: (Transition: TM, TS, TF) × (mode pair) × (pilot group) hover task.
[a]Significant at the 1% level.

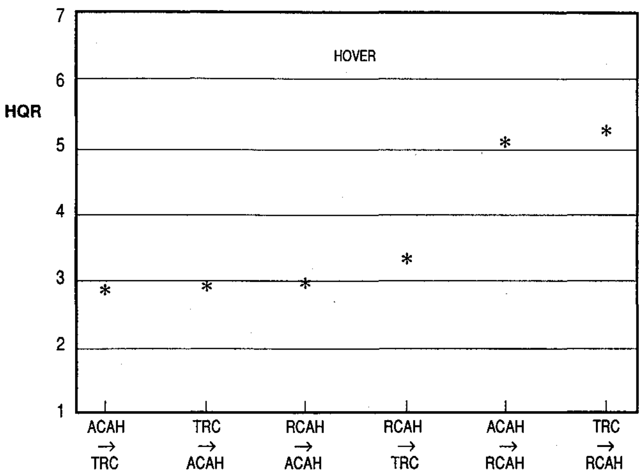


**Fig. 12 Mean HQR for hover task.**

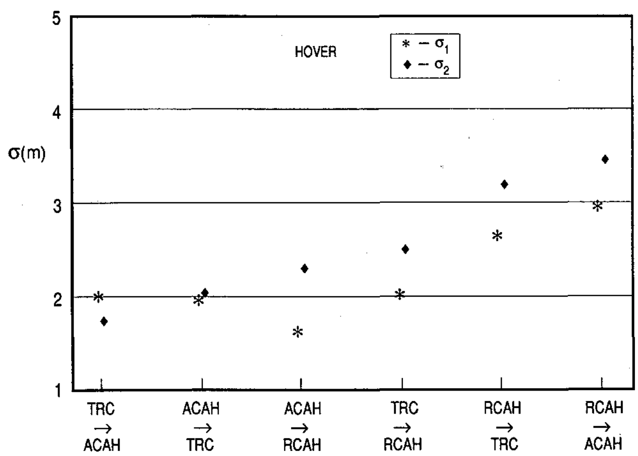


**Fig. 13 Mean performance $\sigma_1$ and $\sigma_2$ for hover task.**

The ANOVA results for the hover task HQR data are presented in Table 4. In this case both mode pair and pilot groups are significant at the 1% level. Again, there are no significant interactions. The trend in the data with mode pair can be seen in Fig. 12. Those ending in RCAH have the poorest ratings, and those starting in RCAH have the next poorest ratings. The effect of the factor pilot group was the same as in the formation task (see Fig. 8). The same test applied to $\sigma_1$ for the hover task showed mode pair to be significant at the 5% level and pilot group to be significant at the 1% level. There were no significant interactions. The trend of $\sigma_1$ with respect to mode pair can be seen in Fig. 13 with the largest $\sigma_1$ values corresponding to mode pairs starting with RCAH.

When the ANOVA was applied to the $\sigma_2$ data, mode pair was significant at the 5% level, and pilot group was significant at the 1% level. There were no significant interaction effects. The trend of $\sigma_2$ with respect to mode pair can be seen in Fig. 13. As in the formation task, mode pairs starting with RCAH produced the poorest performance after mode transition. Mode pairs ending with RCAH tended to have the next poorest performance.

## Conclusions

Within the limitations of the reported study (i.e., one based on HQRs and stationkeeping performance as measured in a helicopter flight simulator) the following conclusions are postulated.

1) The lack of significant effects due to transition type indicates that the degree of pilot awareness concerning the details of a FCS mode transition may not be a dominant factor in determining HQR and performance following transition. This reaffirms the highly successful adaptive nature of the well-trained human pilot.

2) The HQR assigned to a configuration following a FCS mode transition depends to some extent on the HQR of the FCS mode employed prior to the transition. In particular, for the same final FCS mode, initial modes with poorer HQRs tend to cause poorer HQRs to be assigned to the final mode.

3) The tracking performance following a FCS mode transition $\sigma_2$ can be strongly influenced by the FCS mode employed prior to the transition. If the initial mode has poor handling qualities, then the tracking performance after the mode transition will often be unexpectedly poor. In fact, it was found that the FCS mode with the poorest HQR (RCAH in the present study) contributed more to degraded $\sigma_2$ when it was the initial mode, rather than when it was the final mode.

4) In the present study, well-trained pilots (without flight test backgrounds) produced the same ranking for the various helicopter configurations as active test pilots. Any one of the three pilot groups ($G_1$, $G_2$, $G_3$) acting alone would have generated the same experimental results. However, if absolute HQRs are required, then only active test pilots should be used.

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